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LCA OF WASTE MANAGEMENT SYSTEMS

Environmental evaluation and comparison of selected industrial scale biomethane production facilities across Europe

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Abstract
Purpose The two main reasons for producing biomethane as renewable fuel are reduction of climate impacts and depletion of fossil resources. Biomethane is expected to be sustainable, but how sustainable is it actually? This article contributes to the clarification. Therefore, the environmental impacts of several biomethane facilities all over Europe were assessed. A special focus is put on the differences between the facilities as they follow different production routes.
Methods The method used for evaluation is life cycle assessment (LCA) applied in a well-to-wheel approach. This enables to show the overall performance in terms of global warming potential (GWP), acidification potential (AP), eutrophication potential (EP), photochemical ozone creation potential (POCP) and PE fossil. The system boundary includes the entire chain from biogas production to upgrading, distribution and use. For evaluating the different production routes several years of measuring data, calculating and improving the LCA models in close cooperation with the plant operators were carried out.
Results and discussion The evaluation of the production routes shows a high reduction potential compared to fossil fuels. Regarding the depletion of fossil resources, the amounts vary between the sites, but the reduction is at least 50 % and reaches almost 100 % reductions at some sites. The reduction of GWP is at least 65 %, because waste flows free of environmental burdens are used almost exclusively as substrate. Other dominant factors are power and heat demand, methane losses to the environment and the use of by-products, e.g. fertilizer.
Conclusions Despite this caveat, the evaluated systems demonstrate the possible positive results of renewable fuel production if done properly.

Keywords Biofuels · Biogas · Biogas plants · Biogas upgrading · Biomethane · Energy · LCA · Transportation

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1 Introduction

Biogas is generally considered to be environmentally friendly as most renewable energies, but how much is the benefit really? A life cycle assessment (LCA) of biomethane from selected plants across Europe was conducted. "Biomethane" describes upgraded and purified biogas. It is called biomethane to distinguish it from raw biogas due to its high methane content.

As part of a 5-year effort, the European Union created a network of biogas demonstrations, production sites and research facilities. Environmental categories as global warming potential and eutrophication potential were used to assess the activities at various biomethane production sites and compare them to fossil natural gas and diesel. Major technical activities related to the biomethane production system were included, such as the following:

- Feedstock provision
- Biogas production
- Biogas upgrading
- Biomethane distribution
- Biomethane usage

Every site within the project was unique regarding feedstock, production technology, upgrading and distribution.

Although various sites were evaluated, this study only represents large-scale (2,500,000 to 9,750,000 Nm^3 biogas per year) industrial biomethane production sites.

2 System analysis of biomethane production

The whole biomethane production route consists of several steps. These steps are described first in general and then in detail for the specific sites in this study.

2.1 Generic biomethane production routes

The *feedstock* can be organic waste, sewage sludge or various kinds of biomass (Fig. 1). For biogas *production*, bacteria degrade the feedstock in an anaerobic environment. This anaerobic digestion produces biogas that consists roughly of two-third methane and one-third CO_2 by volume, as well as impurities (Fachagentur Nachwachsende Rohstoffe 2010a). The bacteria require a mesophilic (20–45 °C) or thermophilic (>45 °C) environment (Römpp and Falbe 1995) with the ideal range for mesophilic bacteria between 37 and 42 °C (Fachagentur Nachwachsende Rohstoffe e.V. 2010b). The next step after production is *upgrading*, where CO_2 and impurities are removed from the biogas until it is technically identical to natural gas. Several possibilities are available for the upgrading process: physical scrubbing, e.g. water or polyglycol scrubbing; chemical scrubbing using an amine solution or a membrane; cryogenic separation or pressure swing absorption (Urban et al. 2009). *Distribution* can be accomplished via truck in special trailers or by pipeline. Using the truck, the biomethane can either be gaseous or liquid. Liquid transport is only used for long distances due to the high effort required for liquefying the biomethane (Lozanovski et al. 2010). Pipeline transport requires, for example, a dedicated pipeline or an existing low or medium pressure gas grid. Finally, the *use* of biomethane is identical to natural gas, e.g. in vehicles, combined heat and power plants (CHP), boilers or any other technology using natural gas.

2.2 Details of the assessed biomethane production routes

An overview of key figures of the six biomethane production routes investigated is given in Table 1. All of the sites mentioned in Table 1 were part of a European Network to demonstrate the possibility of using biomethane as vehicle fuel. So, there was primary data collected at these sites. Only deviation is the Gothenburg plant. The biogas production site was not part of the project, but as it was the only upgrading plant using an amine scrubber it was decided to include the upgrading.

The feedstock was almost exclusively organic waste and sewage sludge. Only in Västerås, 23 % of the feedstock was deliberately grown as ensilaged ley crop. The full environmental burdens of growth, harvest and silage are therefore attributed to the ley crop used in Västerås. The ley crop was not part of the scope of the study as it was only present at one small site; hence, it is not investigated in detail but accounted for. Sewage sludge and organic waste were considered as waste. No environmental burden was taken into account regarding waste flows. The waste flows currently have no monetary value. If the monetary value or the demand grows, allocation of environmental burdens may need to be revised.

Most of the biogas was produced under mesophilic conditions at 37 to 38 °C, although one production facility works at 57 °C. These temperatures had to be kept constant as the bacteria work best at this temperature and can die if the deviation is too great. Consequently, digesters are generally heated. Heat was obtained from biogas, landfill gas or via fossil fuel combustion; one plant draw heat from their local district heating system (Table 2). Depending on laws and regulations, residues may or may not be used as fertilizer (Hahn and Hoffstede 2010). In Switzerland and Sweden, the residue from sewage sludge digestion was not used as fertilizer due to the high content of heavy metals and other toxic substances. Forbidding residue fertilization thereby attempts to prevent heavy metal accumulation and release of pollutants in the fields and into the waterways. Stockholm and Bern used sewage sludge as a feedstock. In Stockholm, the residue was used as inert material for filling old mine shafts. Bern delivered the dried residue to a cement kiln where it replaced fossil fuels. Lille, Västerås and Linköping used the residue as fertilizer.

Most of the plants were optimized to deliver as much biomethane as possible. At Linköping, even fossil fuels were used for the heat demand of the digester. All sites had a biomethane-to-biogas ratio between 0.60 and 0.68 Nm^3 biomethane per Nm^3 biogas. Only Bern was at 0.19 Nm^3 per Nm^3 as the Bern site wanted to be 100 % self-sufficient not only for the biomethane production but for the whole wastewater treatment plant. The biogas was not used only for heating the digester, but also for drying sludge, heating of other parts of the wastewater treatment plant and heating the office buildings. The majority of the plant's energy demand was covered by biogas. Grid electricity was only used for peak shaving of high loads.

In the upgrading stage, CO_2 was removed from the biogas and released to the environment. Both water scrubbers and pressure swing adsorption plants need mostly electric power. Chemical absorption uses only little electricity but has a high heat demand (Beil and Hoffstede 2010). The heat has to be supplied as steam; so, low-temperature waste heat is not an option.

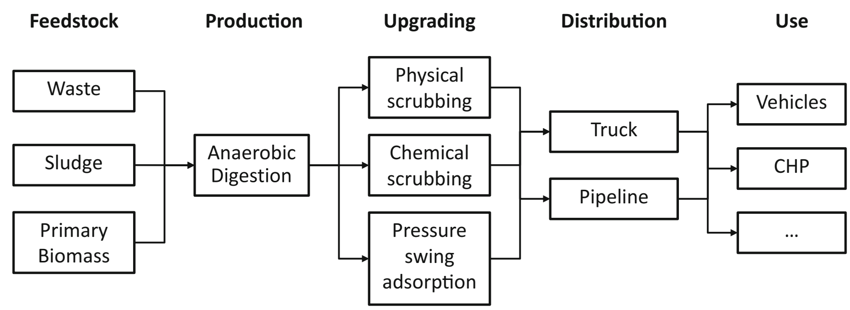


Fig. 1 Schematic overview of different biomethane production routes

The *distribution* was done by pipeline or truck. The biomethane was only transported over short distances not exceeding 10 km. Depending on the pressure levels needed, compressors of different sizes were necessary.

The biomethane was used as vehicle fuel. Natural gas vehicles use the biomethane in internal combustion engines. In the demonstration, network public filling station operators as well as fleet operators are included. Various types of vehicles from normal passenger cars to buses and trucks were fuelled with the biomethane.

3 Method and LCA-specific issues of biomethane production

3.1 Goal of the study

Biomethane production is a complex and interrelated system with, e.g. waste as feedstock, producing fuel and fertilizer as a by-product. For comparison with vehicle fuels, a well-to-wheel study is conducted. Well-to-wheel means that the life cycle chain from production (well) through subsequent

Table 1 Specific overview of the biomethane production sites

	Lille (FR)	Stockholm (SE)	Västerås (SE)	Linköping (SE)	Gothenburg (SE)	Bern (CH)
Feedstock [t/year]	Organic waste (>100,000)	Mainly sewage sludge, fat, food waste (sludge: 750,000)	Organic waste, fat and grass silage (total 23,000)	Slaughterhouse waste, organic waste (total 46,000)	Here the Stockholm site is substituted for biogas production	Sewage sludge, organic waste, waste from chemical plant (sludge: 260,000)
Digester volume [m^3]	3×7,900	5×5,000 2×7,000	2×4,000	2×3,700		3×10,000
Biogas production [Nm^3/year]	7,300,000	9,750,000	2,500,000	7,500,000		9,000,000
Methane content [%]	55	65	65	68		65
Residue use	Fertilizer	Mine filling	Fertilizer	Fertilizer		Secondary fuel in cement kilns
Upgrading	Water scrubbing	Water scrubbing	Water scrubbing	Water scrubbing	Chemical Absorption	Pressure Swing Adsorption
Biomethane produced [Nm^3/y]	4,400,000	6,450,000	1,550,000	5,100,000	5,000,000	1,700,000
Distribution	Bus depot on-site and grid injection	2-km pipeline to bus depot and by truck	8-km pipeline to bus depot	Grid injection	Grid injection	Grid injection
Use	Buses	Buses, public filling stations	Buses	Buses, public filling stations	Buses, public filling stations	Buses, public filling stations

Table 2 Dry matter content in the slurry fed into the digesters

	Lille (FR)	Stockholm (SE)	Västerås (SE)	Linköping (SE)	Bern (CH)
Heat generation source	Biogas	District heating	Landfill gas	Natural gas	Biogas
Dry matter in the slurry [%]	6	2.5	9	6.2	3.7

upgrading and distribution up to the use in the car (wheel) is analysed. This allows biomethane to be compared with fossil fuels, such as natural gas or diesel. This study is accompanying a European Demonstration Project. The goal of this project was to demonstrate biomethane as vehicle fuel. Hence, all results in this article are related to the use as vehicle fuel and raw biogas usage, other biomethane usage possibilities are not part of this article.

3.2 Scope of the study

The functional unit was "1 km bus trip" according to the well-to-wheel approach. Two biogas production sites were located at wastewater treatment plants (Stockholm and Bern) using mainly sewage sludge as feedstock, while other plants utilized organic waste. Figure 2 shows a schematic overview of all flows at all sites. At each site, only some of the shown flows are in use. For example, the biogas production at the wastewater treatment plants uses only sewage sludge, power and heat as inputs for the anaerobic digestion. The biomethane well-to-wheel system is afterwards compared to fossil natural gas and diesel.

Being a renewable fuel, the biomethane has a biogenic CO_2 intake through the feedstock. Biogenic CO_2 is naturally recycled carbon and therefore part of the short-term CO_2 cycle between nature and society. This means that CO_2 passes through the system and is considered to have no net global warming potential. The same amount of CO_2 that is brought into the system is bound in the organic material and is released again at different stages of the system (Lindner et al. 2010). This effect is shown in Fig. 3 where the light grey bars indicate the CO_2 intake in the feedstock as negative and the release of the same amount of CO_2 during the upgrading and use.

Another topic during performing the LCA was that the anaerobic digestion had two products: biogas and digester residue. This multi-functionality was addressed by giving credits for the by-product. Stockholm used the residue as mine filler and therefore did not receive any credit. The Bern site delivers the residue to a cement kiln and receives a credit for the displacement of fossil fuel (Wellinger et al. 2010). The other sites produce fertilizer from the residue and were credited according to the nitrogen, phosphorus and potassium content and the respective amount of replaced industrially produced fertilizer. This amount was calculated based on the Phyllis database for biomass and waste (Phyllis 2014). The credit was given for all impact categories under evaluation and was based on the mineral fertilizer production in the GaBi database (PE and LBP 2014). This fertilizer production is based on best available technology documents from the European Fertilizer Manufacturers Association and the International Fertilizer Industry Association (EFMA 2014; IFA 2014).

The heat generation has a high impact during the biogas production and was therefore investigated in detail. Generally, the impact of heat demand has two major aspects:

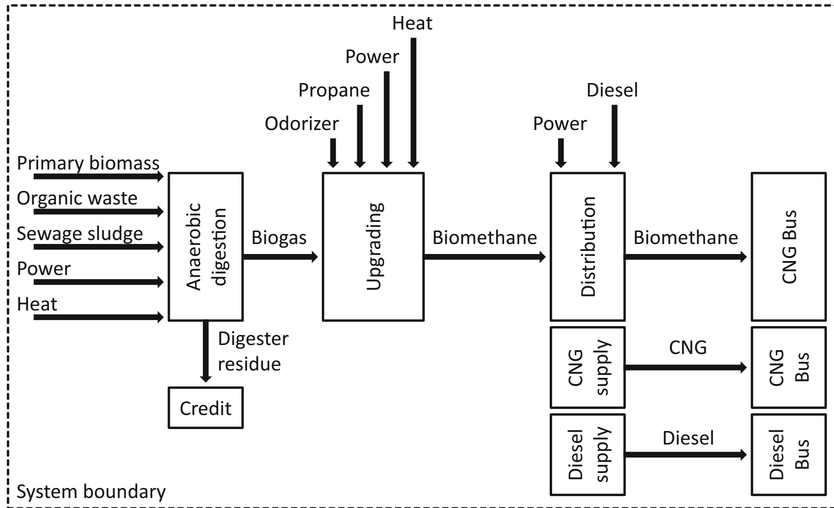
- Type of heat generation (see Table 2)
- Overall heat demand.

Heat demand of biogas production varied significantly among the investigated sites: from 1.4 to 4.5 MJ_{th} per Nm^3 of biogas produced. Besides the heat losses to the environment (similar at all sites), the heat demand is determined by dry solid (DS) content in the slurry (Table 2). The slurry consists of (ground) feedstock mixed with water. A low DS content and consequently high water content are good for the handling of slurry (e.g. pumping and stirring). However, as only organic material is digested to biogas, the water in the slurry has to be heated even though it is unproductive inside the digester. For a low heating demand, low water content is advantageous (Hellstadt et al. 2010). Most of the plants using organic waste had to add water in order to be able to handle the slurry. At wastewater treatment plants, sewage sludge already had high water content; so, the sludge could be thickened.

Power was the primary requirement for upgrading by water scrubber and pressure swing adsorption, and therefore, the impact is related to the country-specific power grid. The chemical absorption in Gothenburg used little electricity but had a high heat demand (Beil and Hoffstede 2010). The heat in the Gothenburg upgrading plant was supplied by a boiler using natural gas. At the time being, the waste heat of the Gothenburg upgrading was not used; a neighbouring facility was planned which should use the waste heat.

Life cycle impact assessment methods used for environmental evaluation are global warming potential (GWP), acidification potential (AP), eutrophication potential (EP) and photochemical ozone creation potential (POCP) (CML 2011). Additionally, the fossil primary energy demand was evaluated.

Fig. 2 System boundary



3.3 Data collection

All sites delivered high-quality primary data. Data from the different production steps were collected, including the operation of biogas production, upgrading, filling stations and vehicle fleets. The data were collected in three stages:

1. Ex-ante data collection: one-time-only questionnaire including information on design data and basic facts
2. Data collection during operation: questionnaires for operating data and for daily measurements
3. Ex-post data collection: one-time-only questionnaire for changes on design data and basic facts.

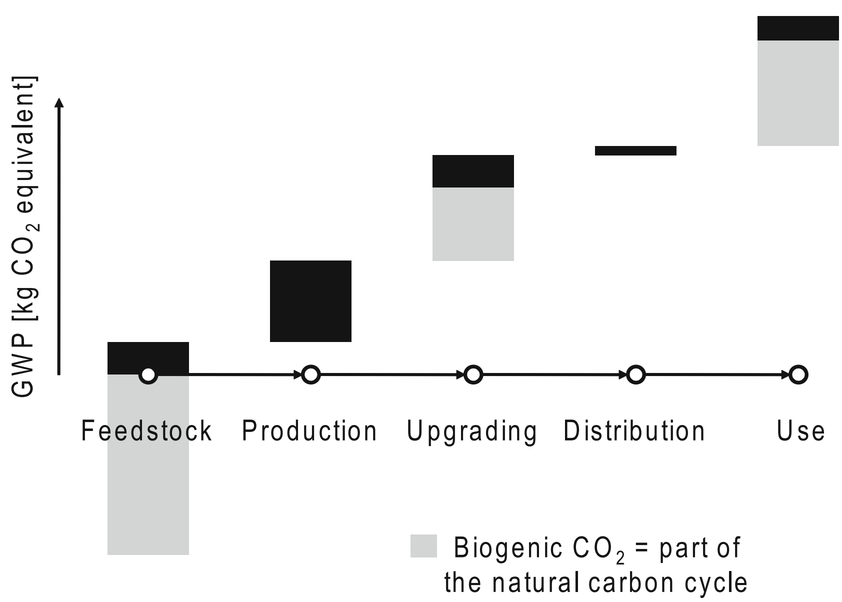
The data were directly measured at the production facilities. The following was achieved with respect to data quality

- High representativeness as primary data were obtained directly from the studied systems
- High completeness by involving the plant operators and by cross-checking during visits and with documents such as the utility bill
- Pre-verification by the data collector
- More than 1 year of operation covered.

Based on these data, site-specific models were created in the GaBi software (PE and LBP 2014) in close cooperation with the operators at the sites.

A specific challenge was the continual optimization and development of the production systems throughout the project duration. The latest complete data were used for the results presented in this paper. For example, the Stockholm site changed its heat supply from on-site biogas combustion to

Fig. 3 Life cycle greenhouse gas emissions of biomethane (schematic)



district heating. Minor differences such as changing the feedstock supplier (as contracts expired) impacted the results only little.

The biogas production of the Gothenburg site was not part of the data collection only the upgrading plant delivered primary data. As it was the only upgrading plant using an amine scrubber, it was decided to include the upgrading also without the production. The Gothenburg upgrading plant was supplied by an existing wastewater treatment plant and another planned biogas production facility that was not finished yet. Since the Gothenburg wastewater treatment plant is approximately the same size and has similar design parameters as the Stockholm plant, the latter was used as a proxy for biogas production within the well-to-wheel analysis of Gothenburg (Lozanovski 2008).

3.4 System comparison

The different biomethane production routes were compared, as well as with fossil fuels (natural gas and diesel). At most sites, biomethane is used in public transport; therefore, a standard 12-m bus commonly used all over Europe was chosen. Most of the buses in Europe run on diesel; so for the comparison, there were two buses, one fuelled by natural gas and the other fuelled by diesel. The emission profile and fuel consumption of these buses were measured in the same facility using the same boundary conditions (Decio 2007). The buses used for evaluation were above Euro 5, so called enhanced environmentally friendly vehicles (EEV). Since all the facilities were evaluated using the same buses, the systems were directly compared.

4 Results

According to the well-to-wheel approach, the functional unit is “1-km bus trip”. Therefore, all results in this chapter are shown as impact per 1-km bus trip. Figure 4 shows the results for net GWP (IPCC 2007). It is evident that one of the major goals is fulfilled: GWP is reduced at least 65 % compared to fossil fuels. There are differences between the sites which show the impact due to the variation in technologies. The overall range for biomethane is in between 0.2 and 0.5 kg CO_2 equivalents per km compared to 1.35 kg CO_2 equivalents per km with diesel.

Figure 5 shows the GWP contributions of the life cycle phases to the net results. The special approach at the Bern site is clearly visible. More emissions are produced during the production phase as more biogas is burned on-site in order to run the system, but the burning of biogas does not contribute to the net GWP as it emits only biogenic CO_2, which is compensated for by the corresponding CO_2 credit. It is also visible that the residue credit has small impact on the overall results.

As the methane slip has a high impact on the GWP, a sensitivity analysis was performed. For this analysis, the

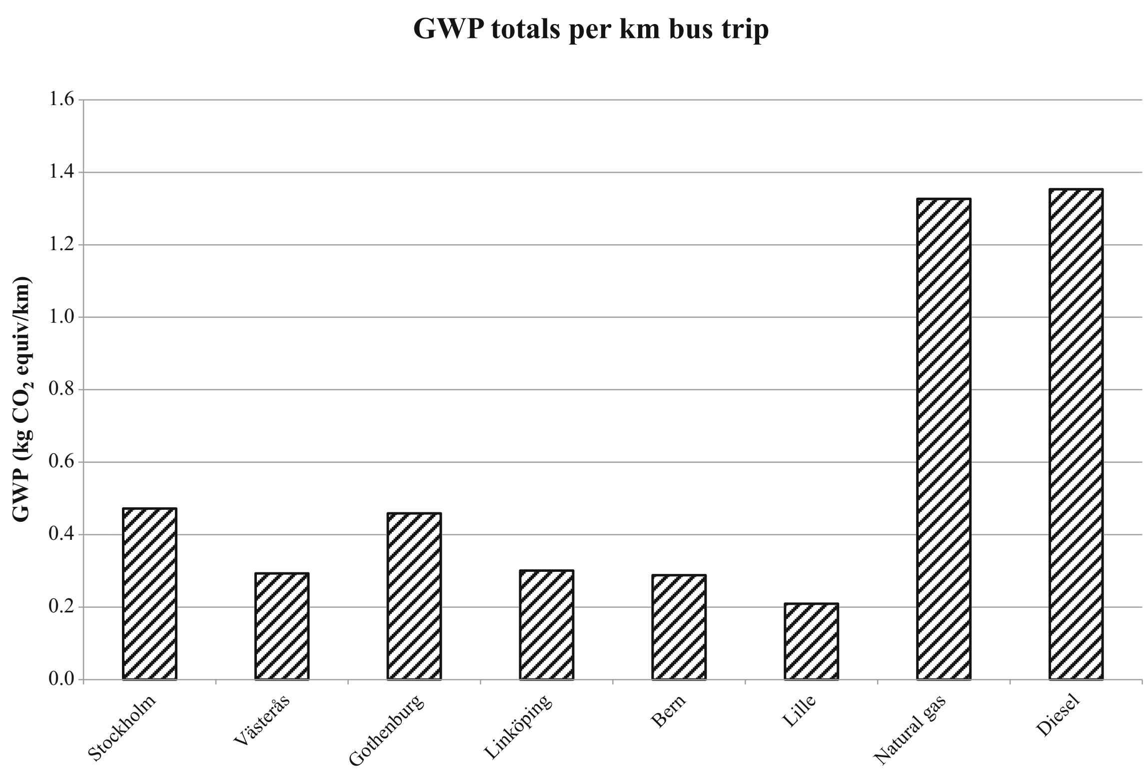


Fig. 4 Net life cycle GWP emissions for the biomethane production sites and for fossil fuels

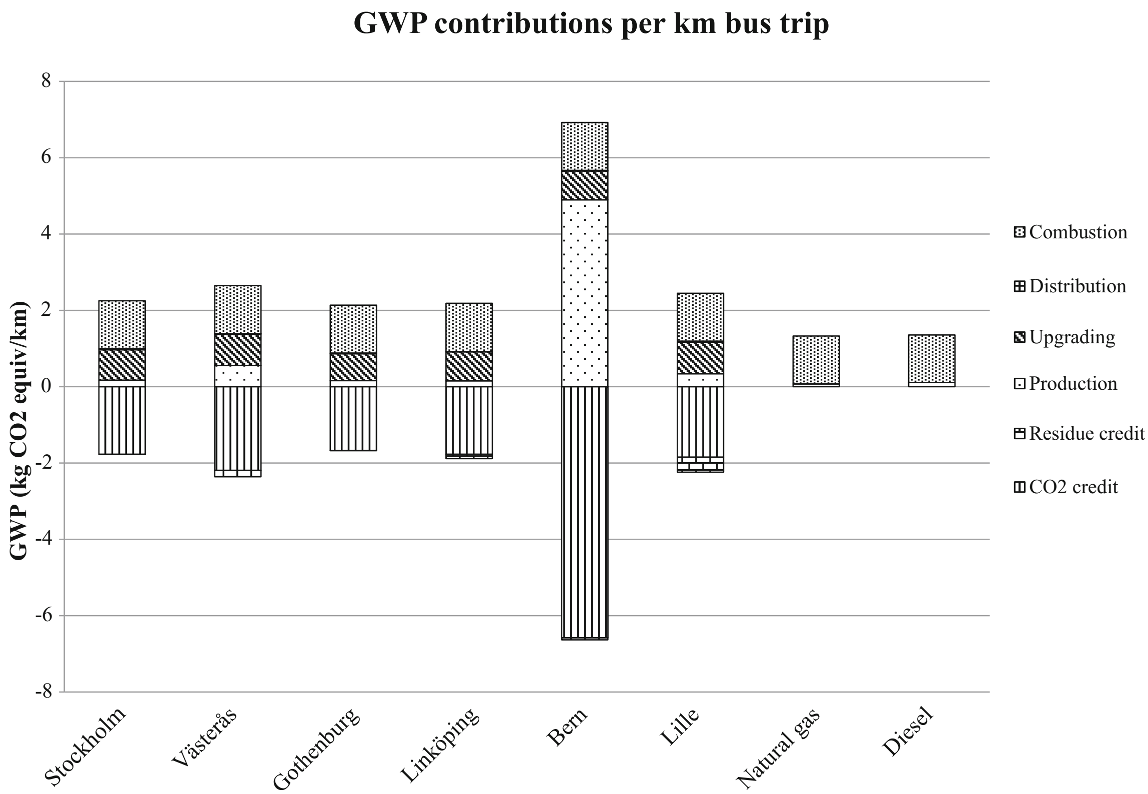


Fig. 5 GWP contributions of the individual life cycle phases for biomethane production sites and for fossil fuels

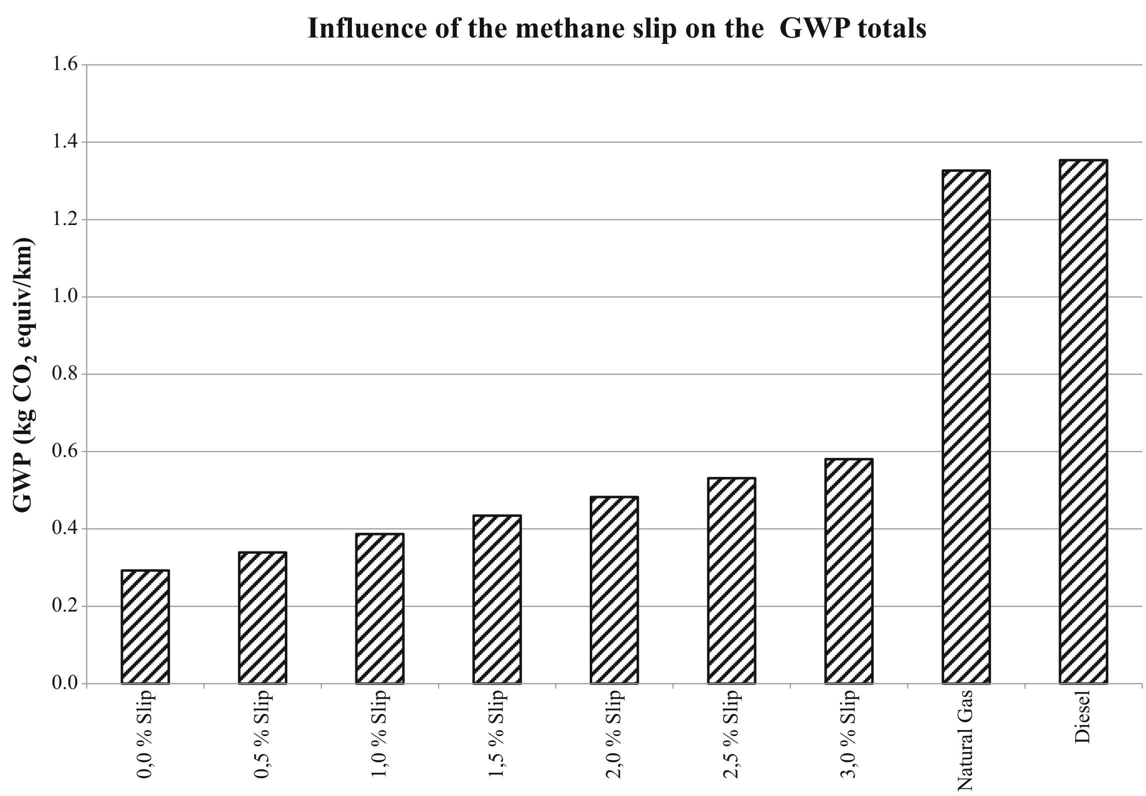


Fig. 6 Sensitivity analysis showing the impact of the methane slip on the GWP totals

Table 3 Impact assessment results of the biomethane and natural gas sites per 1 km of bus trip

Country	Site	Category	CO_2 credit	Residue credit	Production	Upgrading	Distribution	Combustion	Total	Percentile
SE	Stockholm	GWP	−1.77	−0.01	0.17	0.80	0.02	1.26	0.47	36 %
SE	Stockholm	AP	0	−4.2E-05	5.4E-04	6.5E-05	8.5E-05	2.5E-03	3.2E-03	114 %
SE	Stockholm	EP	0	−8.3E-06	2.7E-04	6.5E-06	1.2E-05	4.7E-04	7.4E-04	154 %
SE	Stockholm	POCP	0	−2.6E-06	4.3E-05	5.5E-05	7.5E-06	1.3E-04	2.3E-04	134 %
SE	Stockholm	PE_fossil	0	−0.14	3.47	2.23	1.33	0.00	6.89	31 %
SE	Västerås	GWP	−2.19	−0.17	0.56	0.82	0.02	1.26	0.29	22 %
SE	Västerås	AP	0	−9.6E-04	8.5E-04	6.3E-05	5.2E-05	2.5E-03	2.5E-03	91 %
SE	Västerås	EP	0	−1.8E-04	4.5E-04	6.2E-06	6.5E-06	4.7E-04	7.4E-04	154 %
SE	Västerås	POCP	0	−6.3E-05	6.5E-05	3.7E-05	4.3E-06	1.3E-04	1.7E-04	100 %
SE	Västerås	PE_fossil	0	−3.36	2.66	2.16	1.24	0.00	2.70	12 %
SE	Gothenburg	GWP	−1.67	−0.01	0.16	0.71	0.01	1.26	0.46	35 %
SE	Gothenburg	AP	0	−4.0E-05	5.1E-04	1.9E-04	3.6E-05	2.5E-03	3.2E-03	116 %
SE	Gothenburg	EP	0	−7.8E-06	2.5E-04	2.3E-05	3.6E-06	4.7E-04	7.4E-04	153 %
SE	Gothenburg	POCP	0	−2.5E-06	4.1E-05	3.8E-05	2.8E-06	1.3E-04	2.1E-04	120 %
SE	Gothenburg	PE_fossil	0	−0.13	3.28	5.46	1.23	0.00	9.84	45 %
SE	Linköping	GWP	−1.77	−0.11	0.16	0.76	0.01	1.26	0.30	23 %
SE	Linköping	AP	0	−6.3E-04	2.8E-04	7.4E-05	3.4E-05	2.5E-03	2.3E-03	82 %
SE	Linköping	EP	0	−1.2E-04	7.5E-05	7.4E-06	3.4E-06	4.7E-04	4.3E-04	89 %
SE	Linköping	POCP	0	−4.0E-05	2.7E-05	3.7E-05	2.6E-06	1.3E-04	1.6E-04	90 %
SE	Linköping	PE_fossil	0	−2.12	3.39	2.57	1.19	0.00	5.02	23 %
CH	Bern	GWP	−6.58	−0.06	4.89	0.76	0.01	1.26	0.29	22 %
CH	Bern	AP	0	−8.7E-05	3.8E-03	3.1E-05	2.8E-05	2.5E-03	6.2E-03	226 %
CH	Bern	EP	0	−8.0E-06	1.0E-03	2.7E-06	2.4E-06	4.7E-04	1.5E-03	306 %
CH	Bern	POCP	0	−6.3E-06	1.9E-04	4.0E-05	1.9E-06	1.3E-04	3.5E-04	202 %
CH	Bern	PE_fossil	0	−35.07	6.78	1.19	1.05	0.00	−26.06	−118 %
FR	Lille	GWP	−1.85	−0.39	0.34	0.83	0.02	1.26	0.21	16 %
FR	Lille	AP	0	−2.2E-03	1.5E-03	1.1E-04	8.4E-05	2.5E-03	1.9E-03	70 %
FR	Lille	EP	0	−4.3E-04	1.9E-04	9.1E-06	6.6E-06	4.7E-04	2.5E-04	51 %
FR	Lille	POCP	0	−1.5E-04	1.2E-04	3.2E-05	5.6E-06	1.3E-04	1.4E-04	82 %
FR	Lille	PE_fossil	0	−7.90	5.28	2.81	2.05	0.00	2.24	10 %
SE	Natural gas	GWP	0	0	0.07	0	0	1.26	1.33	
SE	Natural gas	AP	0	0	2.5E-04	0	0	2.5E-03	2.8E-03	
SE	Natural gas	EP	0	0	1.6E-05	0	0	4.7E-04	4.8E-04	
SE	Natural gas	POCP	0	0	4.4E-05	0	0	1.3E-04	1.7E-04	
SE	Natural gas	PE_fossil	0	0	22.01	0	0	0.00	22.01	
SE	Diesel	GWP	0	0	0.11	0	0	1.24	1.35	
SE	Diesel	AP	0	0	5.9E-04	0	0	4.3E-03	4.9E-03	
SE	Diesel	EP	0	0	5.6E-05	0	0	8.0E-04	8.5E-04	
SE	Diesel	POCP	0	0	1.3E-04	0	0	1.9E-04	3.2E-04	
SE	Diesel	PE_fossil	0	0	19.76	0	0	0.00	19.76	

Stockholm plant was used as basis, and the methane slip was varied in between 0 and 3 %. Figure 6 shows that the methane slip has a major impact on the overall results regarding the GWP. The lower the methane slip, the better, but even with 3 % methane slip, the overall environmental performance is still better than using fossil fuels. Higher methane slips should not occur as long as the biomethane production is done properly.

Table 3 shows the site-specific results with regard to the impact categories GWP, AP, EP, POCP (CML 2011) and fossil

primary energy demand (PE_{fossil}). GWP for the evaluated well-to-wheel studies is consistently lower than GWP for fossil fuels. This changes when taking a closer look at AP, EP and POCP. Once again, it is obvious that the Bern approach stands out among the others; the usage of the digester residue as replacement for the provision of fossil fuel for a cement kiln yields only noteworthy credits for GWP and PE, resulting in a GWP for biomethane of 16 to 36 % that of natural gas and diesel. The overall PE_{fossil} for Bern is negative due to credits received; however, the AP, EP and POCP impacts are higher for biomethane than those for the fossil fuels. For all sites, AP of biomethane is generally in the range of 70 to 116 % of the fossil fuel AP; only Bern stands out at 226 %. EP ranges from 70 to 154 % with Bern at 306 %. POCP ranges from 90 to 134 % while Bern is at 202 %.

5 Discussion

Substituting natural gas or diesel with biomethane contributes to a reduction of GWP and PE_{fossil}; however, the remaining impact categories are often greater for biomethane than those for diesel and natural gas. The impact on AP, EP and POCP is partly derived from the biomethane production and partly from the bus operation. Regarding the production part of the impact can be reduced via desulphurisation and more efficient heat generation and usage. The bus operation is the same for all sites. This allows for comparability of the sites. The emission levels of the bus in terms of CO, NO_x and hydrocarbons have a major impact on the AP, EP and POCP. Also, CNG buses emit more hydrocarbons (which include methane emission) compared to the diesel buses. Hence, the direct exhaust methane emission is included. Other possible methane emissions, like during refuelling for example, were unknown during the course of this study but might influence the result too. The buses used in this study were EEV vehicles (above Euro 5). If Euro 6 buses would have been used, the emission levels would be lower. As diesel buses are more commonly used and more time and money is spent on their development, the gap in the environmental profile of diesel buses compared to biomethane buses might increase leading to a higher difference of CNG buses to diesel buses.

The most important data regarding biomethane production are the heat and electricity demand of biogas production and upgrading. If electricity and heat were generated on site using biogas in a CHP or boiler, this was better than using fossil fuels in terms GWP and PE_{fossil}. But, as these small-scale facilities lack comprehensive post-treatment of the exhaust gases, mostly the NO_x and SO_2 emissions influencing AP, EP and POCP were higher compared to those of fossil fuel-driven large-scale power plants and heat generation.

The unique approach of Bern is clearly visible in the results. While the other plants were designed for biomethane production, Bern was designed to produce biomethane and to provide heat and energy to the associated wastewater treatment plant. This interconnected system did not allow for individual accounting of the biomethane. A fraction of the emissions are actually related to the provision of heat and energy to the plant, but the major fraction should be related to the biomethane production and sludge drying. However, it could not be defined further as the heat demand was not measured by the plant operators.

Another important factor is the methane loss. It is difficult to measure as it normally occurs in the exhaust gases of the upgrading facility but sometimes also as diffuse emissions. None of the upgrading facilities had measurement equipment for the methane loss. Therefore, it is taken into account by the design parameters provided by the producer and verified by calculating the carbon balance of the system. Depending on the site, the methane loss varied from 0.1 to 2 %.

The biomethane was mostly delivered to bus depots or filling stations within 10 km of the production facilities. If the biomethane industry were to expand, the transport distances may increase, and hence, the emissions for transport would likely also rise.

The system boundaries are another crucial point of LCA studies. One of the main questions was how the feedstock is taken into account. Most of the feedstock was treated as waste and therefore does not have any environmental burden. If deliberately grown biomass was used, to which an environmental burden is attributed, it is expected that the results would change significantly. The credit for the digester residue also influences the results; it is justified as long as it reflects the real use of the residue. As the credit was based on the nitrogen, phosphorus and potassium contents which are calculated based on literature, it would be recommended for upcoming studies to take samples and calculate the credit based on the measurements.

6 Conclusions

The overall results show that using organic waste and sewage sludge is an efficient way of producing biomethane. Advantages of biomethane over fossil fuels include a reduction in GWP of at least 65 % and a reduction of fossil resources expressed by the PE_{fossil} of more than 55 %. In the case of the Bern site which aims for 100 % self-sufficiency, the net PE_{fossil} is even negative.

Most sites are unique and adapted to the regional circumstances, and so, comparison is not always straightforward. Some feedstocks, for example, contain more energy to

facilitate the production process. However, it is not justified to only use energy-rich feedstock; the feedstock available in the region should be used rather than not using it at all. Other parameters, such as DS content in the biomethane slurry, were compared and resulted in an optimization of the different production sites.

Generally, the biomethane production showed potential to reduce GWP emissions as a renewable fuel. There is still optimisation potential, but it is already obvious that biomethane will be a part of the future energy and fuel mix as the GWP results compared to fossil fuels are promising.

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